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Prediction of the maximum acceptable weight of lift from the frequency of lift

A.D.J. Pinder*, M.G. Boocock [1]

Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire SK17 9JN, UK

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ABSTRACT

It is known that maximum acceptable weight of lift (MAWL) decreases as the frequency of lifting increases. The purpose of this study was to quantify the relationship between lifting frequency and the MAWL, and to generate models for predicting the mean MAWLs for males and females from frequency of lifting. Published experimental studies that have reported the MAWL at different lifting frequencies were identified and regression methods were used to evaluate the relationship between the frequency of lifting and the MAWL. The best fitting models were logarithmic but they accounted for less than 50% of the variance. This reflects the heterogeneity of the experiments included. Normalising the MAWL to the MAWL at one lift per minute improved the predictive power of the models, accounting for more than 80% of the variance. Linear and power models for predicting work rate in kg/min showed even higher levels of accuracy.

Relevance to industry: The paper presents simple mathematical models that can be used to predict the MAWL or the rate of handling weight at a specific frequency. Therefore, they can be used as job design or evaluation tools.

1. Introduction

One approach that has been very influential in research into controlling the risks arising from manual handling has been the use of psychophysical techniques to determine the "maximum acceptable weight of lift" (MAWL) that individual workers are prepared to handle regularly over a work shift. Numerous papers, (for example Snook and Ciriello, 1991; Ayoub et al., 1978; Mital, 1984a; Wu, 1999; Ciriello et al., 2011), have shown that the MAWL decreases as the frequency of lifting increases. In the late 1990's, the Health and Safety Laboratory (HSL) studied the interaction between the weight and frequency of handling (Pinder, 1997; Boocock et al., 1998). The purpose of that work was to determine whether it is better for a manual handling operation to require the worker to exert a larger force less frequently or a smaller force more frequently and therefore, for a constant handling rate (measured in kg min^{-1} for lifting), whether it is better to handle small loads frequently, or large loads infrequently. The first stage was a literature review (Pinder, 1997), which was followed by an experimental study (Boocock et al., 1998). Boocock et al. (1998) summarised the findings of the two studies as pointing,

> "towards a reduction in the weight of lift and increase in the frequency of handling, particularly when the lifts are infrequent (around 3 times a minute or less) and the load is close to the maximum acceptable to the individual (e.g. within the ranges of weights selected by subjects in this experiment)".

The literature review (Pinder, 1997) identified many models for predicting maximum acceptable weights as a function of lifting frequency, and other variables, such as anthropometry, or static strength. The experimental data were combined with the data identified in the literature review to generate logarithmic models that used the lifting frequency to predict both the MAWL and the MAWL relative to the MAWL at one lift per minute (Boocock et al., 1998). In addition, linear models were generated to allow lifting frequency to be used to predict handling rate and handling rate relative to one lift per minute (Boocock et al., 1998). In all cases, separate models were reported for males and females. A wide

* Corresponding author. Tel.: +44 1298 218353; fax: +44 1298 218394.
E-mail addresses: Andrew.Pinder@hsl.gov.uk (A.D.J. Pinder), mark.boocock@aut.ac.nz (M.G. Boocock).
[1] Current address: Health and Rehabilitation Research Institute, Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand. Tel.: +64 99219999; fax: +64 99219620.

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Table 1
A summary of the experimental studies identified by the literature search.

Experiment no.	Source publication(s)	No of subjects	Gender	No of lift frequencies	Other independent variables studied in the experiment(s)
1	Aghazadeh (1985, 1986)	9	M	2	Container type, vertical lift region
2	Aghazadeh et al. (1993)	11	M	5	Lifting vs. lowering
3	Asfour et al. (1985)	10	M	6	Vertical lift region
4	Boocock et al. (1998)	9	M	4	Container shape
5	Chen et al. (1992)	10	M	4	Trunk rotation
6	Chen (2000)	22	M	3	Vertical lift region
7	Chen (2003a)	24	M	3	Vertical lift region, lifting vs. lowering
8	Chen (2003b)	20	M	2	Vertical lift region, abdominal belt tightness
9	Cheng and Lee (2003)	10	M	3	Asymmetry
10	Ciriello and Snook (1978)	15	M	4	Vertical lift region
11	Ciriello and Snook (1983)	10	M	8	Lift distance
12	Ciriello et al. (1990)	10	M	2	Lifting vs. lowering
13	Ciriello et al. (1993)	6	M	2	Vertical lift region, box size, use of handles
14	Ciriello et al. (1993)	6	M	2	Horizontal reach
15	Ciriello et al. (2008)	23	M	3	Lifting vs. lowering, vertical lift region
16	Danz and Ayoub (1991, 1992)	5	M	3	None
17	De la Vega et al. (2009)	22	M	2	Posture when lifting
18	Fernandez and Ayoub (1987, 1988), Fernandez et al. (1991)	12	M	2	Lift duration
19	Founooni-Fard and Mital (1993), Mital et al. (1994)	10	M	5	Lifting vs. lowering
20	Garg and Saxena (1979)	6	M	4	Posture when lifting
21	Garg and Banaag (1988)	8	M	3	Asymmetry, vertical lift region
22	Han et al. (2005)	10	M	2	Asymmetry
23	Hoff and Waly (1998)	10	M	2	Back belt type
24	Jiang and Smith (1985)	12	M	3	Vertical lift region
25	Karwowski and Ayoub (1984)	9	M	4	None
26	Khalil et al. (1987)	12	M	3	Posture when lifting, vertical lift region
27	Lee and Chen (1996a; 1996b)	22	M	3	Box size, vertical lift region
28	Lee et al. (1995)	12	M	4	Vertical lift region
29	Mital (1984a)	37	M	4	Box size, vertical lift region, 12 h shifts
30	Mital (1984b)	37	M	4	Box size, vertical lift region, 8 h shifts
31	Mital (1987a)	10	M	3	Load Centre of Gravity (CG) offset
32	Mital (1987b)	37	M	4	Box width, vertical lift region
33	Mital and Ayoub (1980)	73	M	6	Vertical lift region
34	Mital and Fard (1986)	18	M	3	Box size, CG offset, vertical lift region, asymmetry
35	Mital and Kumar (1997)	12	M	3	Box size, vertical lift region
36	Mital and Manivasagan (1983)	10	M	3	Material density, CG offset, hand preference
37	Mital and Wang (1989)	8	M	2	Shelf clearance, vertical lift region
38	Singh et al. (2002)	7	M	3	Vertical lift region, mental arithmetic task
39	Singh et al. (2009)	30	M	6	Obesity, gender, vertical lift region
40	Snook (1971)	28	M	7	Lifting (vs. lowering)
41	Snook (1971)	28	M	5	Lowering (vs. lifting)
42	Straker and Cain (2000)	13	M	1	Posture when lifting
43	Wright and Mital (1998)	20	M	4	Vertical lift region, age
44	Wu (1997)	13	M	4	Box size
45	Wu (1999)	29	M	2	Vertical lift region
46	Yates and Karwowski (1987)	8	M	2	Sitting and standing
47	Zhu and Zhang (1990)	8	M	5	Posture when lifting
48	Boocock et al. (1998)	9	F	4	Container shape
49	Ciriello and Snook (1983)	12	F	8	Lift distance
50	Ciriello and Snook (1983)	12	F	3	Object size, lift distance
51	Ciriello and Snook (1983)	12	F	3	Box size
52	Ciriello et al. (1990)	12	F	2	Lifting vs. lowering
53	Ciriello (2005)	10	F	2	Lifting vs. lowering, vertical lift region, lift distance, box size
54	Ciriello (2007)	10	F	9	Vertical lift region, box size, horizontal reach
55	Ciriello et al. (2011)	24	F	3	Lifting vs. lowering, vertical lift region
56	De la Vega et al. (2009)	17	F	2	Posture when lifting
57	Karwowski and Yates (1984)	6	F	2	Liquid contents
58	Karwowski and Yates (1986)	7	F	4	Liquid contents
59	Khalil et al. (1987)	5	F	3	Posture when lifting, vertical lift region
60	Maiti and Ray (2004)	18	F	1	Vertical lift region, work group
61	Mital (1984a)	37	F	4	Box size, vertical lift region, 12 h shifts
62	Mital (1984b)	37	F	4	Box size, vertical lift region, 8 h shifts
63	Mital (1987b)	37	F	4	Box width, vertical lift region
64	Mital and Ayoub (1980)	73	F	6	Vertical lift region
65	Mital and Wang (1989)	8	F	2	Shelf clearance, vertical lift region
66	Morrissey et al. (1990)	4	F	4	Asymmetry of lift
67	Singh et al. (2009)	30	F	6	Obesity, gender, vertical lift region
68	Straker and Duncan (2000)	17	F	1	Posture when lifting
69	Wright and Mital (1998)	20	F	4	Vertical lift region, age
70	Wu (1999)	12	F	2	Vertical lift region

Table 2
Absolute MAWLs (kg) reported for males and females at different frequencies.

Exp. No.	One lift	Frequency (lifts per minute)																											
		0.002	0.033	0.1	0.2	0.5	1	2	3	3.8	4	4.3	4.6	5	5.5	6	6.7	7	7.5	8	9	10	11	12	14	16	18	20	22
Male																													
1								27.4								23.1													
3							27.2		20.0					18.6				15.8			14.8		13.3						
4	40.1						21.5					16.3												10.1					
5							27.5	25.3			20.2									15.8									
6	37.0						25.4				19.9																		
7	35.8						24.3				18.5																		
8	37.0										18.6																		
9							18.8	17.2			15.5																		
10		59.0					37.7					33.0					29.5												
11		52.5	46.5		44.0	41.0	37.5					29.5					25.5							20.0					
12							36.7					32.5																	
13							19.7					18.5																	
14							16.8					17.1																	
15							19.8					17.5												12.7					
16							35.7				27.5									17.8									
17		31.9					20.1																						
18								22.1												12.2									
19																									12.2	10.4	10.2	9.8	8.6
20									20.5							17.5					14.7			12.4					
21									28.2							24.5					21.3								
22							17.3							13.9															
23								18.8								16.5													
24	59.6						35.5									24.7													
25				47.8					29.9												19.3			15.1					
26								18.1			16.4					15.8													
27	34.4						23.9				18.7																		
28	34.3						23.2				18.5					16.8													
29							11.8				10.8									9.5				8.1					
30							14.9				13.7									12.1				10.6					
31								21.0			19.7					18.6													
32							12.7				11.7									10.9				10.5					
34							18.1				16.8									15.3									
35							18.6									17.0								15.1					
36								21.0			19.4					18.7													
37							19.8				16.9																		
38								7.6			7.9									6.9									
39		32.6	27.6				21.7					18.7					17.2											15.3	
40							23.4			21.1		20.4	18.8		20.2	16.8	19.3												
41							24.3					22.5					17.5		19.5			15.4							
42												10.1																	
43					16.8		15.1	14.1			12.0																		
44	41.7						32.4				27.2					23.7													
45		30.4			21.4																								
46							12.5				10.7																		
47								17.2	15.6		14.8			13.8		12.4													
Mean	40.0	41.3	37.1	47.8	27.4	41.0	23.1	19.1	22.8	21.1	16.9	21.5	18.8	15.4	20.2	18.9	21.8	15.8	19.5	12.6	17.5	15.4	13.3	12.7	12.2	10.4	10.2	12.5	8.6
SD	7.8	12.0	9.5		11.9		7.6	5.1	5.4		4.8	6.9		2.3		3.7	4.9			3.4	2.9			3.4				2.7	
N	8	5	2	1	3	1	30	11	5	1	21	11	1	3	1	13	5	1	1	8	4	1	1	9	1	1	1	2	1

(*continued on next page*)

Table 2 (*continued*)

Exp. No.	One lift	Frequency (lifts per minute)																												
		0.002	0.033	0.1	0.2	0.5	1	2	3	3.8	4	4.3	4.6	5	5.5	6	6.7	7	7.5	8	9	10	11	12	14	16	18	20	22
Female																													
48	24.8						13.9					12.1												8.1					
49		21.5	17.5		15.5	16.0	14.0					12.5					11.5							10.0					
50							17.7					17.7					15.0												
51							15.6					15.0					13.2												
52							13.4					12.8																	
53							14.2					11.6																	
54		24.6	15.4		16.4	14.6	11.6					10.2					10.7							8.6				6.0	
55							10.4					9.2												6.8					
56		13.5					8.5																						
57											11.5									9.1									
58							13.2		11.9							9.6								8.2					
59								7.6			7.4					7.0													
60							16.1																						
61							9.9				9.1									7.9				7.5					
62							11.0				10.3									9.2				8.7					
63							10.2				9.6									8.8				8.5					
65							13.5				11.8																		
66						24.7	22.2		20.8								16.4												
67		20.9	19.0				16.3					14.3					12.6											12.2	
68														7.8															
69					6.3		5.6	4.7			4.3																		
70		16.4			11.6																								
Mean	24.8	19.4	17.3		12.4	18.4	13.2	6.2	16.3		9.1	12.8		7.8		8.3	13.2			8.8				8.3				9.1	
SD		3.9	1.5		4.0	4.5	3.7	1.4	4.5		2.4	2.4				1.3	2.0			0.5				0.9				3.1	
N	1	5	3	0	4	3	18	2	2	0	7	9	0	1	0	2	6	0	0	4	0	0	0	8	0	0	0	2	0

range of frequencies was included in the models, but the experimental studies included were quite heterogeneous because of the diverse independent variables studied in conjunction with frequency.

The purpose of this paper is to report updated models to predict the MAWL and maximum acceptable handling rate from the frequency of lift. These models were produced using the results of an updated literature search that identified experimental studies published since the original study, (Boocock et al., 1998).

2. Methods

2.1. Search strategy for the literature review

A Reference Manager (Thomson-Reuters, New York) database used within HSL to store references relating to manual handling and musculoskeletal disorder (MSDs) was used as the initial source of references for the updated literature search. This database contains the results of the previous literature review (Pinder, 1997). It is updated regularly with citations obtained from searches of the PubMed and Excerpta Medica electronic databases. These searches use a combination of keywords designed to identify occupational studies of human posture, manual force, and manual handling. Psychophysical studies of manual handling are explicitly sought. Peripherally relevant articles are included, rather than excluded. The results of *ad hoc* searches of the Ergonomics Abstracts on-line, NIOSHTIC2, CISDOC and HSELINE databases have also been included. Tables of contents of ergonomics and related journals are scanned as issues are published and relevant references are added. The database also contains relevant references from the Proceedings of the Human Factors and Ergonomics Society (HFES) annual conference, the triennial International Ergonomics Association (IEA) congress, the triennial PREMUS (Prevention of Work-Related Musculoskeletal Disorders) conference and the annual conference of the Institute of Ergonomics and Human Factors (IEHF). It is not restricted to articles published in the English language, but non-English databases are not searched when it is updated. No limits on publication date are used, but few articles predate the creation of the MEDLINE database in 1965.

Our database was searched for reports of psychophysical experiments involving manual handling published since the previous review was completed in 1997 using the terms (and their variants) “frequency”, “maximum acceptable weight” and “psychophysics”. Similar searches were carried out on the PubMed and Ergonomics Abstracts on-line databases and relevant references were merged into the Reference Manager database. Titles and abstracts of the papers found by the search strategy were reviewed and relevant papers were retrieved and read as were relevant papers identified from the reference lists of these papers. The database contains approximately 3700 references that refer to manual handling. Of these approximately 840 refer to MAWL, frequency, or psychophysics. After elimination of papers that did not report experimental measurement of MAWL, 59 papers were included in the literature review.

2.2. Data extraction and statistical analysis

When an experimental study was identified as reporting the MAWL, the mean MAWLs for males and females were tabulated separately for each reported frequency of lift. Where separate MAWLs were reported for different levels of other independent

Table 3
MAWLs (%) for males and females relative to absolute MAWL at 1 lift per minute.

Exp. No.	One lift	Frequency (lifts per minute)																						
		0.002	0.033	0.2	0.5	1	2	3	3.75	4	4.3	4.6	5	5.4	6	6.7	7	7.5	8	9	10	11	12	20
Male																								
2						100%	92%			78%					61%				50%					
3						100%		73%					69%				58%			54%		49%		
4	186%					100%					76%												47%	
5						100%	92%			73%									58%					
6	145%					100%				78%														
7	146%					100%				76%														
9						100%	92%			83%														
10		156%				100%					87%					78%								
11		140%	124%	117%	109%	100%					79%					68%							53%	
12						100%					89%													
13						100%					94%													
14						100%					101%													
15						100%					88%												64%	
16						100%				77%									50%					
17		158%				100%																		
22						100%							81%											
24	168%					100%									70%									
27	144%					100%				78%														
28	148%					100%				80%					73%									
29						100%				91%									81%				69%	
30						100%				92%									81%				71%	
32						100%				92%									86%				83%	
33						100%	97%			91%			89%		88%				80%					
34						100%				93%									84%					
35						100%									91%								81%	
37						100%				85%														
39		151%	127%			100%					86%					79%								70%
40						100%			86%		83%	86%		85%	76%	81%								
41						100%					80%					78%		69%			68%			
43				112%		100%	94%			80%														
44	128%					100%				84%					73%									
46						100%				86%														
Mean	152%	151%	126%	114%	109%	100%	93%	73%	86%	83%	86%	86%	80%	85%	76%	77%	58%	69%	71%	54%	68%	49%	67%	70%
SD	18%	7%	2%	3%		0%	2%			6%	7%		9%		10%	5%			15%				12%	
N	7	4	2	2	1	32	5	1	1	17	10	1	3	1	7	5	1	1	8	1	1	1	7	1

(*continued on next page*)

Table 3 (*continued*)

Exp. No.	One lift	Frequency (lifts per minute)																					
		0.002	0.033	0.2	0.5	1	2	3	3.75	4	4.3	4.6	5	5.4	6	6.7	7	7.5	8	9	10	11	12	20
Female																								
48	179%					100%					87%												58%	
49		154%	125%	111%	114%	100%					89%					82%							71%	
50						100%					95%					88%								
51						100%					93%					88%								
52						100%					95%													
53						100%					82%													
54		180%	112%	120%	107%	100%					93%					78%							63%	47%
55						100%					88%												65%	
56		158%				100%																		
58						100%		90%							73%								62%	
60						100%																		
61						100%				92%									80%				76%	
62						100%				93%									83%				78%	
63						100%				94%									86%				83%	
64						100%	96%			89%			86%		83%				77%					
65						100%				87%														
66					111%	100%		94%								74%								
67		128%	117%			100%					88%					77%								75%
69				112%		100%	85%			76%														
Mean	179%	155%	118%	114%	111%	100%	90%	92%		89%	90%		86%		78%	81%			82%				70%	61%
SD		18%	5%	4%	3%	0%	6%	2%		6%	4%				5%	5%			3%				8%	14%
N	1	4	3	3	3	19	2	2	0	6	9	0	1	0	2	6	0	0	4	0	0	0	8	2

variables, such as the distance through which the load was lifted (Ciriello and Snook, 1983), these variables were tabulated and the mean values reported were averaged across the variable for each frequency. The absolute rate of handling (in kg per minute) was calculated at each frequency as the product of the mean absolute MAWL (in kg) and the frequency of lift (in lifts per minute). Snook and Ciriello (1991) reported using one lift per minute as a criterion rate to compare MAWLs at different frequencies. Where the publication reported the absolute MAWL at this rate, a relative MAWL was calculated as the ratio of the absolute MAWL to the MAWL at one lift per minute. Similarly, the relative handling rate was calculated as the ratio of the absolute handling rate to the handling rate at one lift per minute.

In order to select appropriate regression methods, SPSS v14.0 for Windows (SPSS Inc.) was used to compare possible models for predicting MAWL from frequency of lift. The models included a constant term, i.e. the regression line was not forced to pass through zero. Initially all the models available within the SPSS Curve Estimation option (Linear, Logarithmic, Inverse, Quadratic, Cubic, Compound, Power, S, Growth, Exponential, and Logistic models) were used to predict male MAWL from frequency. The adjusted R^2 values were used to assess the goodness of fit of the models. The same approach was used to compare regression models relating the frequency of lift to the handling rate. As male and female data sets follow the same trends, only data from males were used for this process of selecting appropriate regression methods.

3. Results

3.1. Selection of appropriate methods of regression analysis

For absolute MAWL, a logarithmic model was found to provide the best fit to the data (adjusted $R^2 = 44.7\%$), followed by a power model (adjusted $R^2 = 36.3\%$). A linear model had adjusted $R^2 = 25.3\%$ and inspection of the plotted data showed a non-linear relationship between frequency and MAWL. Further modelling of absolute and relative MAWLs was therefore restricted to logarithmic and power models.

For absolute handling rate, a power model provided the best fit to the data (adjusted $R^2 = 95.7\%$), followed by a cubic model (adjusted $R^2 = 81.3\%$). A linear model had adjusted $R^2 = 75.9\%$. A logarithmic model had adjusted $R^2 = 48.3\%$. For ease of use, the linear model was preferred over the cubic model and further modelling of absolute and relative handling rates was restricted to power and linear models.

3.2. Data used in the models

Table 1 summarises 70 experiments that were identified from the 59 papers included in the current review and for which either absolute or relative MAWL were reported. Of the 70 experiments, 47 used male participants and 23 used females. Some papers reported multiple experiments using the same participants (Snook, 1971; Ciriello and Snook, 1983; Ciriello et al., 1993) and 15 of the 23 experiments that involved females were reported in papers that also reported experiments involving males. As shown in the table, subject numbers in the experiments ranged between five and 73 for males, and between four and 73 for females. The number of frequencies tested per experiment ranged up to eight for males and nine for females.

Table 4
Absolute handling rates (kg per minute) for male and females at different frequencies.

Exp. no.	Frequency (lifts per minute)																											
	0.002	0.033	0.1	0.2	0.5	1	2	3	3.8	4	4.3	4.6	5	5.5	6.0	6.7	7	7.5	8	9	10	11	12	14	16	18	20	22
Male																												
1							55								139													
3						27		60					93				110			133		146						
4						22					70												121					
5						28	51			81									127									
6						25				80																		
7						24				74																		
8										74																		
9						19	34			62																		
10	0.12					38					141					197												
11	0.11	1.6		8.8	21	38					126					170							240					
12						37					140																	
13						20					80																	
14						17					74																	
15						20					75												152					
16						36				110									142									
17	0.07					20																						
18							44												98									
19																								171	167	184	196	189
20								61							105					133			148					
21								84							147					191								
22						17							70															
23							38								99													
24						35									148													
25			4.8					90												174			181					
26							36			66					95													
27						24				75																		
28						23				74					101													
29						12				43									76				98					
30						15				55									97				127					
31							42			79					112													
32						13				47									87				126					
34						18				67									122									
35						19									102								181					
36							42			78					112													
37						20				68																		
38							15			32									55									
39	0.07	0.92				22					80					115											305	
40						23			79		87	87		110	101	128												
41						24					96					116		146			154							
42											43																	
43				3.4		15	28			48																		
44						32				109					142													
45	0.06			4.3																								
46						12				43																		
47							34	47		59			69		74													
Mean	0.09	1.24	4.8	5.5	21	23	38	68	79	68	92	87	77	110	114	145	110	146	101	158	154	146	153	171	167	184	250	189
SD	0.03	0.32		2.4		8	10	16		19	30		11		22	33			27	26			40				55	
N	5	2	1	3	1	30	11	5	1	21	11	1	3	1	13	5	1	1	8	4	1	1	9	1	1	1	2	1

(*continued on next page*)

Table 4 (*continued*)

Exp. no.	Frequency (lifts per minute)																										
	0.002	0.033	0.1	0.2	0.5	1	2	3	3.8	4	4.3	4.6	5	5.5	6.0	6.7	7	7.5	8	9	10	11	12	14	16	18	20	22
Female																												
48						14					52												97					
49	0.04	0.58		3.1	8.0	14					54					77							120					
50						18					76					100												
51						16					64					88												
52						13					55																	
53						14					50																	
54	0.05	0.51		3.3	7.3	12					44					71							103				120	
55						10					39												81					
56	0.03					9																						
57										46									73									
58						13		36							58								98					
59							15			30					42													
60						16																						
61						10				36									64				90					
62						11				41									74				104					
63						10				38									70				102					
65						14				47																		
66					12	22		62								109												
67	0.04	0.63				16					61					84											245	
68													39															
69				1.3		5.6	9.5			17																		
70	0.03			2.3																								
Mean	0.04	0.6		2.5	9.2	13	12	49		37	55		39		50	88			70				99				183	
SD	0.01	0.05		0.8	2.2	3.7	2.8	13		9.7	10				8.0	13			4.0				11				63	
N	5	3	0	4	3	18	2	2	0	7	9	0	1	0	2	6	0	0	4	0	0	0	8	0	0	0	2	0

The absolute and relative MAWLs used in the modelling are presented in Tables 2 and 3, respectively. The absolute and relative handling rates are given in Tables 4 and 5, respectively.

The scatter plots and best-fit regression lines are shown in Figs. 1–4. The best-fit regression equations are given in Table 6. The best-fit equations for absolute MAWL and relative MAWL were found to be logarithmic, i.e. of the form $\mathrm{MAWL} = a + b \times \ln(F)$, where a and b are constants, and F is the frequency of lift in lifts per minute. The proportions of variance in absolute MAWL accounted for by the logarithmic models were relatively low (44.7% for males and 33.7% for females), due to the inherent variability arising from the inclusion of data from experiments where a wide range of independent variables were manipulated. Table 1 lists the other independent variables studied in each experiment. The power (log–log) equations, of the form $\ln(\mathrm{MAWL}) = a + b \times \ln(F)$ or $\mathrm{MAWL} = a \times F^b$ accounted for only 36.3% (males) and 27.3% (females) of the variance in the MAWL.

The equations for relative MAWL accounted for much more of the variability than the equations for MAWL did, with the logarithmic equations accounting for over 80% of the variance, and the power equations accounting for approximately 70% of the variance.

The best-fit equations for absolute handling rate were found to be power equations, i.e. of the form $\ln(\mathrm{handlingrate}) = a + b \times \ln(F)$ or $\mathrm{handlingrate} = a \times F^b$. These accounted for 95.7% of the variance for males and 97.3% of the variance for females. Even so, linear equations for absolute handling rate accounted for 76–85% of the variance.

The best-fit equations for relative handling rate were also power equations and for males left only 0.6% of the variance unaccounted for, and for females left only 0.3% unaccounted for. The linear models for relative handling rate accounted for 93.4% of the variance for males and 94.1% for males.

4. Discussion

The psychophysical measurement of MAWL, as exemplified in the databases published by Snook and Ciriello (1991), has influenced greatly the creation of guidance that attempts to help employers reduce the burden of low back pain. Examples are the "Liberty Mutual tables" (Liberty Mutual, 2012) and the NIOSH Lifting Equations (NIOSH, 1981; Waters et al., 1993) in the USA and official UK guidance on manual handling operations (HSE, 2004). In the light of the importance of the psychophysical approach, and based on an extensive review of the literature, this study has generated mathematical models that permit the prediction of absolute and relative MAWLs and handling rates solely from the frequency of lifting and the gender of the worker. The models for MAWL relative to the MAWL at the one lift per minute criterion frequency explain much greater levels of variance than the model for absolute MAWL because finding the relative MAWL removes much of the variation between the experimental studies reported in the literature.

The degrees of freedom are fewer for relative MAWL models than for those for absolute MAWL because studies that did not include the one lift per minute criterion task were not included. Similarly, the degrees of freedom for the relative handling rate are fewer than for the absolute handling rate.

The power models for absolute handling rate were found to have R^2 values of approximately 96%, which is noticeably better than the linear models. From the graphs of the regressions

Table 5
Handling rates (%) for males and females relative to absolute handling rates at 1 lift per minute.

Exp. no.	Frequency (lifts per minute))																					
	0.002	0.033	0.2	0.5	1	2	3	3.75	4	4.29	4.62	5	5.45	6	6.67	7	7.5	8	9	10	11	12	20
Male																							
3					100%		220%					343%				406%			489%		538%		
4					100%					326%												563%	
5					100%	184%			293%									460%					
6					100%				314%														
7					100%				304%														
9					100%	183%			330%														
10	0.32%				100%					372%					523%								
11	0.29%	4.1%	23%	55%	100%					337%					453%							640%	
12					100%					381%													
13					100%					403%													
14					100%					434%													
15					100%					380%												770%	
16					100%				308%									399%					
17	0.33%				100%																		
22					100%							403%											
24					100%									418%									
27					100%				312%														
28					100%				319%					435%									
29					100%				365%									644%				828%	
30					100%				368%									650%				853%	
32					100%				369%									687%				992%	
34					100%				372%									676%					
35					100%									548%								974%	
37					100%				341%														
39	0.31%	4.2%			100%					370%					530%								1409%
40					100%			323%		357%	395%		462%	458%	540%								
41					100%					342%					518%		520%			682%			
43			22%		100%	187%			319%														
44					100%				335%					439%									
46					100%				343%														
Mean	0.32%	4.2%	23%	55%	100%	185%	220%	323%	333%	370%	395%	373%	462%	460%	513%	406%	520%	586%	489%	682%	538%	803%	1409%
SD	0.01%	0.1%	0.6%		0%	1.8%			25%	31%		30%		46%	31%			113%				148%	
N	4	2	2	1	30	3	1	1	15	10	1	2	1	5	5	1	1	6	1	1	1	7	1
Female																							
48					100%					372%												697%	
49	0.32%	4.2%	22%	57%	100%					383%					548%							857%	
50					100%					405%					584%								
51					100%					378%					586%								
52					100%					410%													
53					100%					351%													
54	0.37%	3.7%	24%	53%	100%					398%					521%							753%	945%
55					100%					378%												778%	
56	0.33%				100%																		
58					100%		271%							440%								746%	
60					100%																		
61					100%				368%									644%				909%	
62					100%				374%									667%				940%	
63					100%				376%									690%				1000%	
65					100%				349%														
66				56%	100%		281%								492%								
67	0.27%	3.9%			100%					376%					516%								1503%
69			22%		100%	169%			306%														
Mean	0.32%	3.9%	23%	55%	100%	169%	276%		355%	383%				440%	541%			667%				835%	1224%
SD	0.04%	0.2%	1%	2%	0%		5%		26%	17%					35%			19%				101%	279%
N	4	3	3	3	18	1	2	0	5	9	0	0	0	1	6	0	0	3	0	0	0	8	2

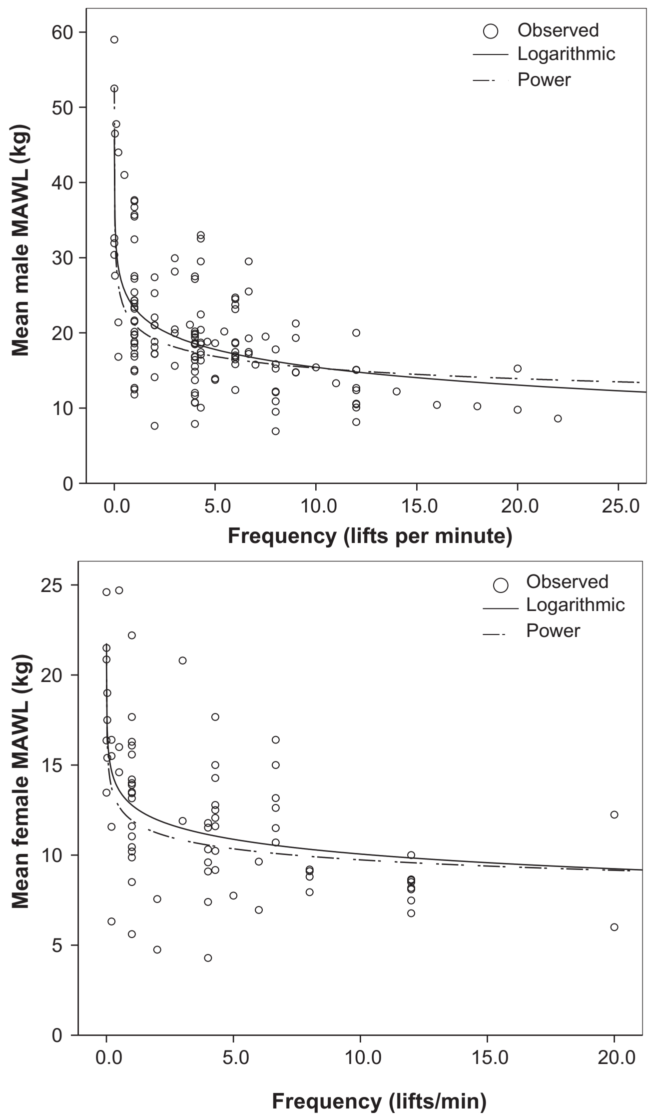

Fig. 1. Scatter plots and regression curves showing the relationships between absolute male and female MAWLs and the frequency of lifting.

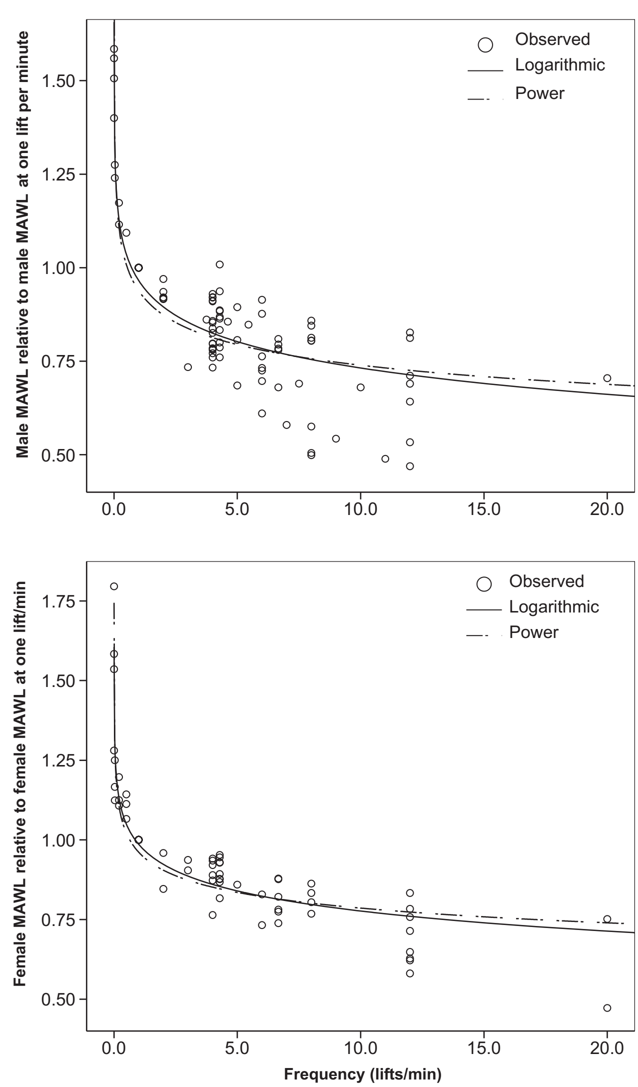

Fig. 2. Scatter plots and regression curves showing the relationships between relative male and female MAWLs and the frequency of lifting.

(Fig. 3), it is clear that these models provide a better fit than the linear model at the lower frequencies. Since the process of calculating absolute handling rate involves multiplying the absolute MAWL by the frequency, it is to be expected that the variance explained by a regression model of absolute handling rate on frequency will be higher than one for absolute MAWL on frequency.

The handling rate models in Table 6 do not take into account differences in the distances through which the loads are lifted. Taking these distances into account would create models predicting work done in Joules and would improve the predictive power of the models by further reducing the variation between the experimental studies. This approach was not pursued as only a few studies (Ciriello and Snook, 1983; Ciriello, 2005) varied the distance of lift rather than the region (such as floor to knuckle height, or knuckle height to shoulder height) in which the lift occurred.

For relative handling rate, the linear models accounted for 93–94% of the variance and the power models accounted for over 99% of the variance. This reflects two factors. Firstly, the calculation of relative values reduces variation between the experimental studies from which the data were extracted. Secondly, the handling rate is a function of frequency and therefore correlates closely with relative handling rates. Again, the power models fit the data at the lower frequencies better than the linear models.

5. Application of the predictive models

The reported models have the advantage of simplicity when predicting the MAWL in that they require only the gender of the worker and the frequency of lift. Therefore, they are easier to use than, for example, the models reported by Genaidy et al. (1990) that include additional factors such as the height of lift, the box size, working time, asymmetry and handles. Because of these additional factors, the R^2 values of the Genaidy et al. (1990) models are much greater than those reported here (83.2% vs. 44.7% for males, 86.0% vs. 33.7% for females). However, our models make use of data from a much wider range of experiments than was available to Genaidy et al. (1990), who used data from Ayoub et al. (1978), Mital (1984a; 1984b) and Snook (1978). There are many

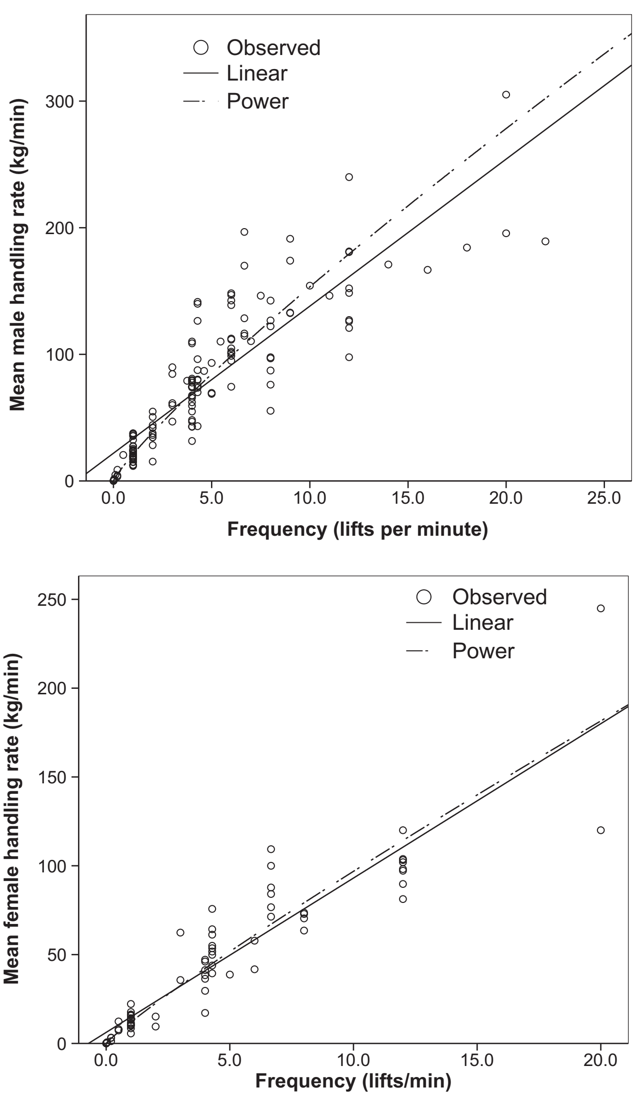

Fig. 3. Scatter plots and regression curves showing the relationships between absolute male and female handling rates and the frequency of lifting.

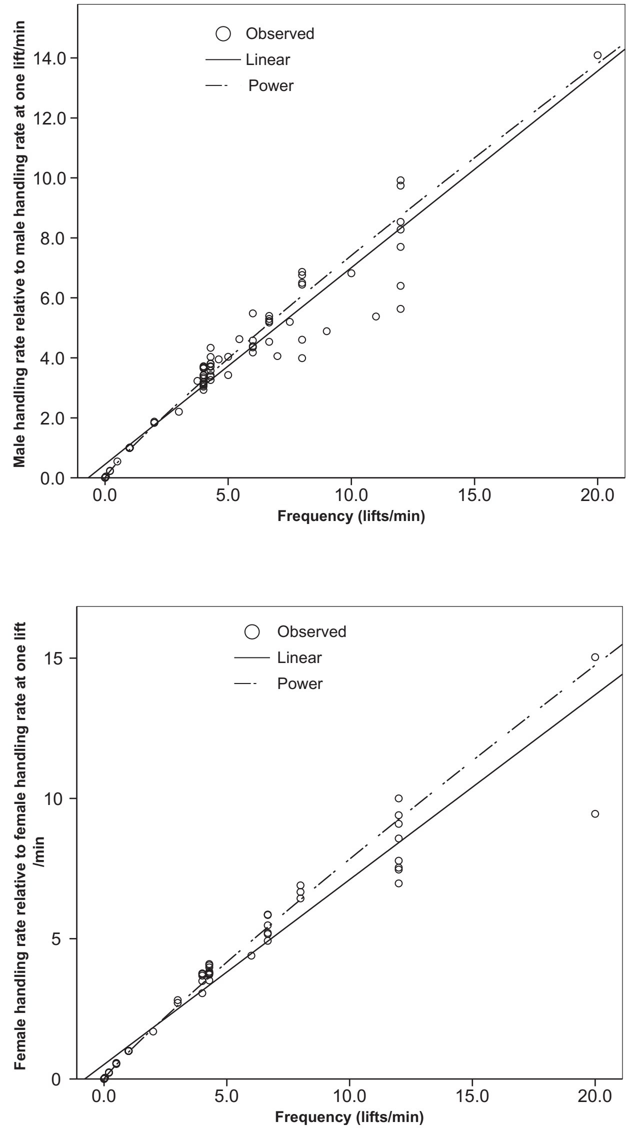

Fig. 4. Scatter plots and regression curves showing the relationships between relative male and female handling rates and the frequency of lifting.

other publications, (for example, Ayoub et al., 1979; Jiang and Mital, 1986; Mital, 1986) that have reported predictive models using frequency and other parameters. In another approach, Mital and Ayoub (1986) reported a model to predict the MAWL that used measurements of isometric strengths and the anthropometry of the individual and that had an R^2 value of approximately 84%.

The most useful of the models reported here are the linear handling rate models as these allow the quantification of the gain in total load handled that can be achieved by increasing the frequency of handling. They are also simpler to use than the power models. However, the power models should be used for handling at low frequencies, as they fit the experimental data better when the frequency of lifting is below two lifts per minute. The relative MAWL and relative handling rate models are useful where data are available for the criterion frequency of one lift per minute.

A practical approach to designing a manual handling task might be to simulate realistic workplace conditions (such as the height range through which the load is lifted) and to determine the MAWL at one lift per minute. Absolute MAWLs at other frequencies could then be predicted with a high degree of accuracy.

Our models can be applied where handling occurs for the duration of a working shift at a fixed or approximately fixed rate but are more difficult to apply in situations where the rates of handling or the loads handled vary. In reality, there are very few real-world jobs that consist solely of lifting fixed weights at fixed frequencies because such jobs are likely to be easily mechanised and lengthy pauses in activity between lifting operations will be seen as unproductive. Therefore, it is likely that other activities will occur between lifts, unless the job is carried out at high rates without pauses between repetitions. These interspersed activities may be tasks, such as inspection, that do not involve handling or physical exertion. However, activities, such as pulling or pushing, which do involve physical exertion, may affect the performance of the workers on the lifting task.

Another issue is that tasks that have fixed cycle times are often machine paced so may not be popular with workers. While such

Table 6
The best-fit equations for using frequency of lift (F) in lifts per minute to predict absolute MAWL, relative MAWL, absolute handling rate and relative handling rate for males and females, based on psychophysical experimental data reported in the literature.

Gender	Model type	Equation	Adjusted R^2	Degrees of freedom
MAWL (kg)				
Male	Logarithmic	$MAWL = 23.294-3.417 \times \ln(F)$	44.7%	1 & 143
Female	Logarithmic	$MAWL = 12.779-1.182 \times \ln(F)$	33.7%	1 & 74
Male	Power (log–log)	$\ln(MAWL) = 21.104-0.139 \times \ln(F)$	36.3%	1 & 143
Female	Power (log–log)	$\ln(MAWL) = 11.931-0.088 \times \ln(F)$	27.3%	1 & 74
Relative MAWL				
Male	Logarithmic	$RelMAWL = 0.966-0.102 \times \ln(F)$	81.0%	1 & 111
Female	Logarithmic	$RelMAWL = 0.986-0.091 \times \ln(F)$	85.6%	1 & 72
Male	Power (log–log)	$\ln(RelMAWL = 0.939-0.104 \times \ln(F)$	66.0%	1 & 111
Female	Power (log–log)	$\ln(RelMAWL) = 0.962-0.088 \times \ln(F)$	77.1%	1 & 72
Work rate (kg/min)				
Male	Linear	$Handlingrate = 21.878 + 11.617 \times F$	75.9%	1 & 143
Female	Linear	$Handlingrate = 6.218 + 8.689 \times F$	85.0%	1 & 72
Male	Power (log–log)	$\ln(Handlingrate) = 21.106 + 0.861 \times \ln(F)$	95.7%	1 & 143
Female	Power (log–log)	$\ln(Handlingrate) = 12.031 + 0.906 \times \ln(F)$	97.3%	1 & 72
Relative work rate				
Male	Linear	$Relhandlingrate = 0.449 + 0.656 \times F$	93.4%	1 & 100
Female	Linear	$Relhandlingrate = 0.518 + 0.659 \times F$	94.1%	1 & 66
Male	Power (log–log)	$\ln(Relhandlingrate) = 0.938 + 0.898 \times \ln(F)$	99.4%	1 & 100
Female	Power (log–log)	$\ln(Relhandlingrate) = 0.959 + 0.912 \times \ln(F)$	99.7%	1 & 66

pacing may be desirable to help balance flows within some work environments, such as production lines, it has downsides due to the monotony of the task and decreased control that the individual worker has over the work.

6. Conclusions

This study used regression methods to generate logarithmic and power models to allow the prediction of mean MAWLs for males and females from the frequency of lift. It also generated linear and power models to predict work rate in kg min^{-1}. The models presented appear to be robust in that they are based on a large number of data points derived from psychophysical experiments that have examined a wide range of lifting frequencies in conjunction with numerous other independent variables. They are not designed to take account of variability in these other variables, such as the height through which the load is lifted.

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